NORMAL WAVE PROPAGATION VELOCITY

IN A STATIC WEB

By

GLEN D. FRANCIS

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1985

Submitted to the Faculty of the
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Oklahoma State University
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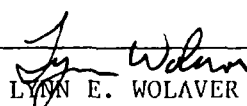Degree of Master of Science
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       The systems currently in use require contact with the web and
       generally produce an average tension measurement across the span
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       propagation velocity with respect to variations of tension. The
       theory is that the normal wave propagation velocity will increase
       with increasing web tension and decrease with decreasing tension.
       Experiments were performed on a static web and incorporated both
       standing and propagating wave techniques. The goal of this
       research was to provide information for the development of a
       device to measure web tension without contacting the web surface
       and which would provide information as to the tension variance
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IN A STATIC WEB

This individual research investigation, INDEN 5350 - Industrial
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ABSTRACT

Web tension measurement and control has been a major problem in web processes since the first conceptual phases of web handling. The systems currently in use require contact with the web and generally produce an average tension measurement across the span of the web. This study investigated the variance of normal wave propagation velocity with respect to variations of tension. The theory is that the normal wave propagation velocity will increase with increasing web tension and decrease with decreasing tension. Experiments were performed on a static web and incorporated both standing and propagating wave techniques. The goal of this research was to provide information for the development of a device to measure web tension without contacting the web surface and which would provide information as to the tension variance across the span of the web.

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CHAPTER I

INTRODUCTION

In the context of this report, the word "web" will refer to any

material in continuous flexible strip form. In normal situations, a

web is very long in comparison to its width and very wide in comparison

to its thickness. Handling processes for such a material present many

ongoing problems to industry world wide. One such problem in web

handling processes concerns the control of tension in the web.

There will commonly be several machines linked together to handle

the web in different processes, or maybe one large machine with

several sections to perform different functions. Each section or

machine may require a different tension to properly do its job. Too

much tension in any one section could break the web and create a

stoppage of the process, while too little tension could prevent the

process from being properly performed. As machine complexity

increases, the need for proper tension control also increases.

Before control of any characteristic of a function can be obtained,

the proper measurement and evaluation of that particular characteristic

must be done.

There re several methods currently in use to measure tension in a

web process. Most use a dancing roller or similar technique. In this

approach, an extra roller is added to the process in such a manner that

it displaces the web. The displaced web will exert more force on the

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roller with an increase in web tension and less force with a decrease in web tension. This force is then measured through the use of a spring, load cell, pneumatic device, or possibly an electro-mechanical sensor. The sensor will send a signal to an indicator which will directly read out the web tension, or to a processor in the tension control loop. These methods can provide an accurate measure of average tension across the web span.

A device called the "Huyck Tensometer" works on the principle that the amount of deflection of the web for a given load is directly proportional to the tension in the web. This device uses a plunger on a spring. The device is pressed against the web surface, and a dial indicator displays the deflection. Thus, this device determines local tensions in a static web.

Another device which is similar to the Huyck Tensometer uses a pad mounted on a pressurized box. The device is pressed against the web and the pressure changes in relation to the amount of tension in the web. This is again based on the fact that a displaced web will exert more force with increased tension and less force with decreased tension. This device gives an average tension over the span of the pad, but it can be moved across the span of the web to provide a tension profile.

The method that this report is concerned with is based on the principle that the velocity of normal wave propagation (sonic velocity) in a web is directly proportional to the square root of the tension of the web. This characteristic was evaluated through two methods. The first dealt with a standing wave in the web. The wave length of the standing wave was longer with decreased tension and

shorter with increased tension. The second dealt with a propagating

wave down the length of the web. This was accomplished by pulsing the

web and measuring the time that the pulse, propagating wave, took to

travel between two points. Increased tension yielded a faster wave

velocity. Either method could be incorporated in a device and

mounted on a traverse to take readings at points across the span of

the web and provide a profile of lateral variations of normal tension.

CHAPTER II

LITERATURE SURVEY

2.1 Tension Measurement

The most primitive way to provide tension to the web is to use a drag belt in contact either with the unwind roll surface,[1] or a brake drum connected to the unwind roll axle. This method was easy to apply, but not always easy to control. Due to the fact that the unwind roll was continually changing in diameter, the torque on the web and the tension in the web were changing. This can be better followed through the understanding of Eq. 2.1. In this equation, T is the torque on the roll, F is the tension force in the web, and

$$F = \frac{T}{r} \qquad\qquad \text{Eq. 2.1}$$

r is the roll radius. When the belt was run against the roll surface, not only was the radius of the roll changing, but the amount of area between the belt and the roll surface was also changing. Thus, the friction force between the belt and the roll was changing giving two variables to monitor during the process. The torque could be held constant by running the belt against a brake drum, but then as the

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[1] Donatas et al., "Web Handling," Web Process and Converting Technology and Equipment New York: Van Nostrand Reinhold Company, 1984), pp. 94-9..

radius decreased, the tension in the web increased. Both methods gave a form of measurement and control to early web processes, but as happens, web handling processes quickly outgrew the basics and required a higher degree of accuracy of measurement and control of web tension.

In his doctoral thesis entitled "Critical Analysis of Portable Web-Tension Measuring Equipment" Ahmed El-Sayed[2] quoted N. Haglov as saying that the ideal web tension regulator should maintain a very accurate web tension within a few percent. This high degree of accuracy has continually created problems for web handling processes.

As El-Sayed outlines in his thesis (pp. 11-16), the most widely used method of obtaining accurate web tension measurements, revolves around the use of a dancer roll or idler roll. Both make use of the fact that a displaced web will exert more force with an increase of tension. However, there is some difference in the actual sending device (Satas, pp. 399-401).

The dancer roll is positioned in such a manner that it displaces the web (see Figure 2.1). The dancer roll then has freedom of movement either in the horizontal or vertical direction, or it moves in an arc. A counter balance is used to minimize the effect of the roll weight and enable the device to obtain a higher degree of sensitivity. When the process requires a low tension, multiple dancer rolls can be used to overcome the effect of inertia on the system.

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[2]Ahmed Ali Mohammed El-Sayed, "Critical Analysis of Portable Web-Tension Measuring Equipment" (Loughborough University of Technology, 1976), p. 11.

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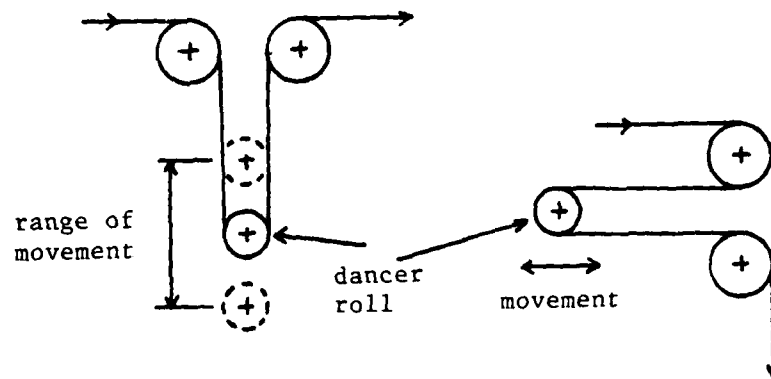
Figure 2.1   Examples of Dancer Roll.

The idler roll (see Figure 2.2) is a stationary roll with strain
gauges, pressure sensors, load cells, or some other similar device
incorporated in the mounting fixture of the roll. A change in tension
of the web creates a change in the force exerted on the roll mount.
The sensors monitor this change in force and send signals to a dial
indicator, digital readout, or control devices in the tension control
loop.

Figure 2.2   Examples of Idler Roll.

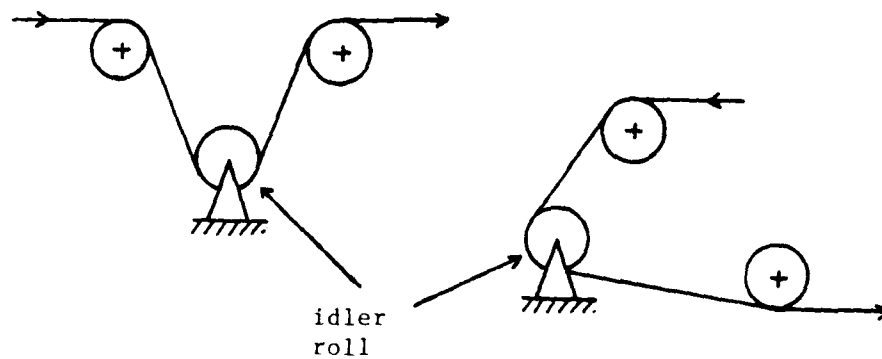These two methods are the most common in industry, however, they leave a gap in the knowledge of what is happening to the web tension. They do an excellent job of measuring average web tension across the span of the web, but they tell nothing about how the tension varies across the web. This knowledge could be very helpful in understanding and controlling such web phenomenon as bagginess, wrinkles, and bubbles.

El-Sayed extensively tested the Huyck tensometer and determined that it did not perform to manufacturer's (Huyck Corporation of U.S.A.) specifications. The device was designed to be used on felt webs in paper mills with a tension range of 0.9 to 4.4 kN/m. Web printing presses standardly operate between 0.1 and 0.5 kN/m, and steel lines may vary from 5 to 500 kN/m (El-Sayed, pp. 138-139). He did not criticize the narrow range, but he did criticize the results he obtained from experimental tests. He found that even in its operation range, the Huyck tensometer output showed obvious nonlinearity. This combined with the facts that the device is for use on static webs and that the output must be converted to force through the use of tables for the particular web material, make the Huyck tensometer useless in many situations.

El-Sayed's major research was to build and test two variations of the same measurement scheme. The major idea again came back to the fact that the higher the web tension is, the more force is required to displace the web. El-Sayed's approach to measure the force was based on the same concept of a pneumatic distance measuring device (see Figure 2.3). A box is equipped with a constant pressure air supply and pressure sensor. As an object (B) gets closer to the box opening,
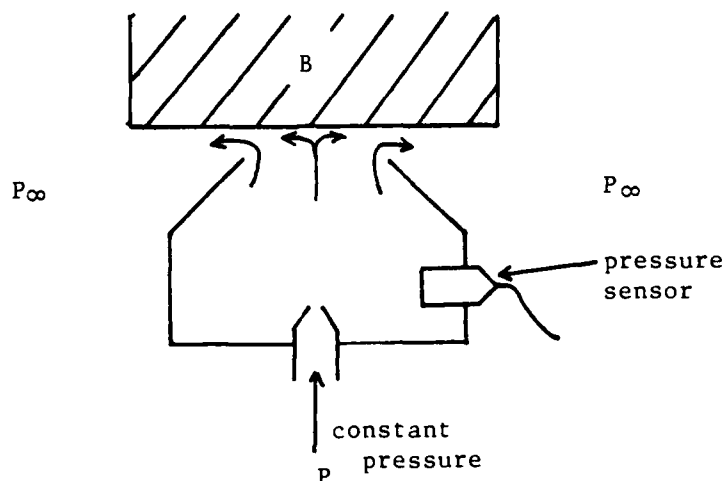
B

P_∞ P_∞

pressure
sensor

constant
pressure
P

Fiqure 2.3 Pneumatic Distance Device.

the pressure in the box increases. Thus, the device can be calibrated

to measure the distance between the box opening and the object. In the

same manner, El-Sayed used a box with a stainless steel wire mesh pad

over the opening. This qave a uniform pressure distribution across the

surface between the web and the device, and acted as an air bearing

between the web and pad. The pad was also curved and an optimum wrap

angle was determined. The pressure sensor was mounted in the center of

the pad. Thus, the pressure measurement of the device would be in

relation to the averaqe tension in the web over the span of the pad.

This mechanism could then be traversed across the web span to provide

a tension profile which El-Sayed averaqed and found to be very accurate

in comparison to the known averaqe tension. He also applied this

concept to a cylinder which was centered on the web. El-Sayed found

both devices to be very accurate under normal web conditions so lonq

as the volume of air in the pneumatic circuit was minimized.

There appear to be no other advancements in the area of tension measuring devices for web handling processes over the past few years. In a 1982 article in Experimental Mechanics, Rolf P. Haggstrom[3] discussed the current tension measuring devices which continue to incorporate the idler roll and dancer roll techniques.

2.2 Sonic Velocity Measurement

A technique for measuring sonic velocity in paper has been used for several years. In 1965, Craver and Taylor[4] analyzed the use of sonic measurements to determine several mechanical properties of paper. They were able to develop a system to determine a "sonic modulus" which could then be used to calculate such properties as tensile strength, elasticity, and directional stresses in the paper.

This approach was also used by Mann, Baum, and Habeger[5] in the development of a system to measure these mechanical properties on line (1979 and 1980). They developed the mathematics together and Baum and Habeger[6] applied the concept. They modified a system that was already

---

[3] Rolf P. Haggstrom, "Experiments on Tension Measurement in Manufacturing Processes," Experimental Mechanics, March 1982, pp. 106-110.

[4] J. K. Craver and D. L. Taylor, "Nondestructive Sonic Measurement of Paper Elasticity," Tappi, vol. 48, no. 3 (March 1964), pp. 142-147.

[5] R. W. Mann, G. A. Baum, and C. C. Habeger, "Determination of All Nine Orthotropic Elastic Constants for Machine-Made Paper," Tappi, vol. 63, no. 2 (Feb. 1980), pp. 163-166.

[6] G. A. Baum and C. C. Habeger, "On-Line Measurement of Paper Mechanical Properties," Tappi, vol. 63, no. 7 (July 1980), pp. 63-66.

in use to determine roll hardness. The approach used a wheel which ran in contact with the web. A piezoelectric element at one spot in the wheel circumference would pulse the web when it came in contact with the web. An identical wheel would then pick up the pulse and translate it into an electrical signal. The signal could then be processed and the measurements made. Wheels mounted in both the machine direction (MD) and the cross-machine direction (CD) were used to gather data for calculation of all nine orthotropic elastic constants.

This research was carried further by Senko and Thorpe[7] to use a "continuous-wave-phase-shift" measurement technique versus what they called the "time-of-flight" technique of Baum and Habeger. Senko and Thorpe found that it was difficult to distinguish the pulse from noise in the web. The continuous-wave-phase-shift approach provided a signal that was easier to detect and the longer time frame for measurement provided for a higher degree of certainty. Their approach utilized a wheel with four piezoelectric crystals each covering 1/4 of the wheel's circumference. Thus, the wave form could be continuously produced in the web, and continuously received by identical wheels. The signal was then processed to determine the phase shift between the transmitting wheel and the receiving wheel. As with Baum and Habeger, two receiving wheels could be used to obtain readings in both MD and CD.

In all of these approaches, sonic velocity can be found through Eq. 2.2 where c is the sonic velocity, E is the modulus of elasticity of the web, and ρ is the web density (kg/m^3). The wave form effected

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[7] E. Senko and J. Thorpe, "On-Line Ultrasonic Measurement of Sheet Modulus," Tappi, vol. 68, no. 2 (Feb. 1985), pp. 95-99.

$$c = \sqrt{\frac{E}{\rho}}$$

Eq. 2.2

by these parameters is internal to the web and deals with particle movement in the web which is similar to electron movement in electrical wire. Typical sonic velocities for this wave form are on the order of 10^3 m/s.

The wave forms that this research deals with induces movement of the entire web (see Figure 2.4). This wave form is much slower and is referred to as a normal wave. Its governing equation is Eq. 2.3 where T is the tension (N/m of width), and σ is the web density (kg/m^2). Although this is a much different wave form, the equipment that has been used in the other research could prove to be quite useful for this approach.
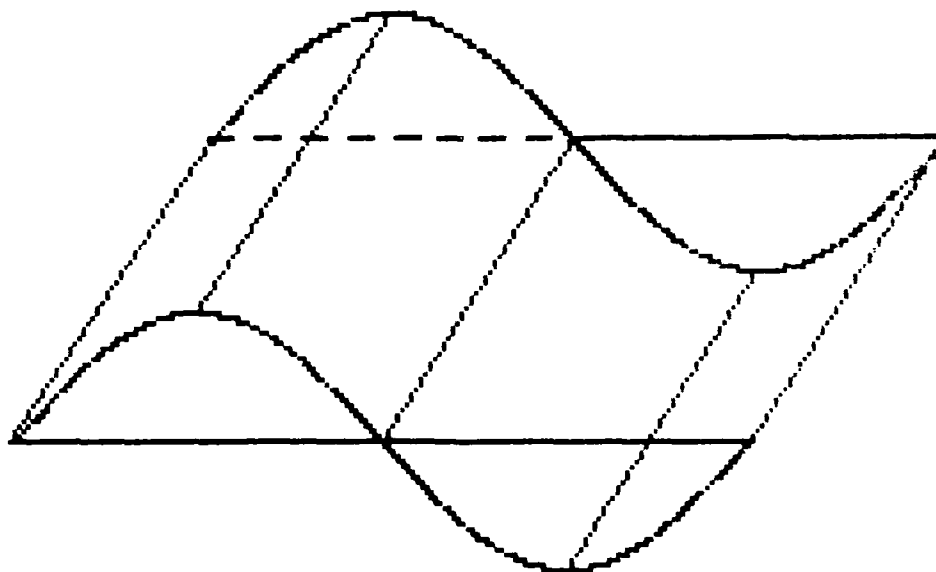

Figure 2.4 Normal Wave.

$$c = \sqrt{\frac{T}{\sigma}}$$

Eq. 2.3

CHAPTER III

METHODS

3.1 Equipment

Most all of the equipment used in this research was common

acoustical research equipment. For the standing wave experiments

(see Figure 3.1), an oscillator was used to power a speaker at several

frequency settings. A microphone and microphone power supply were

connected to an oscilloscope. For the propagating wave experiments

(see Figure 3.2), the pulse signal was produced by the oscillator and

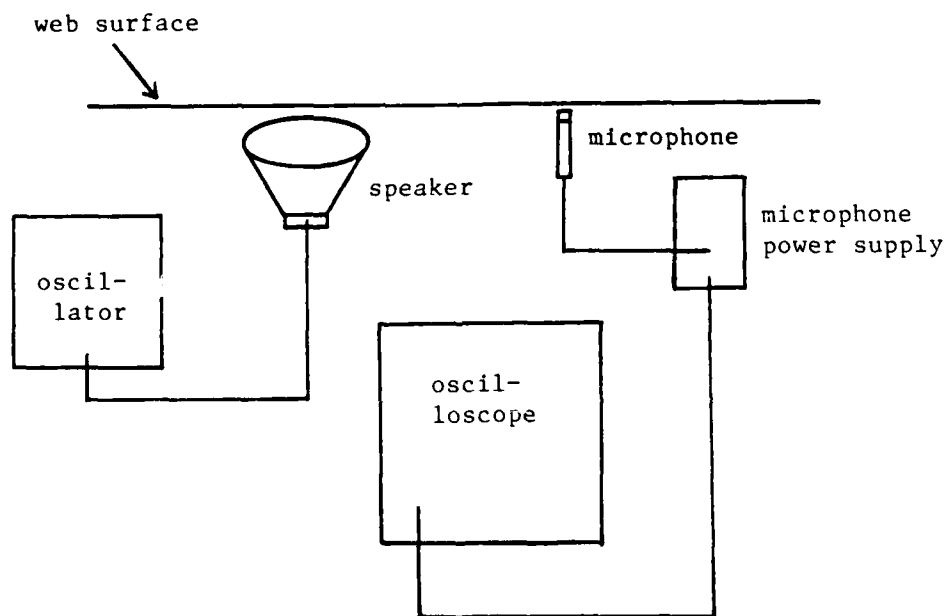gaited by a pulse generator. The pulsed signal was then amplified

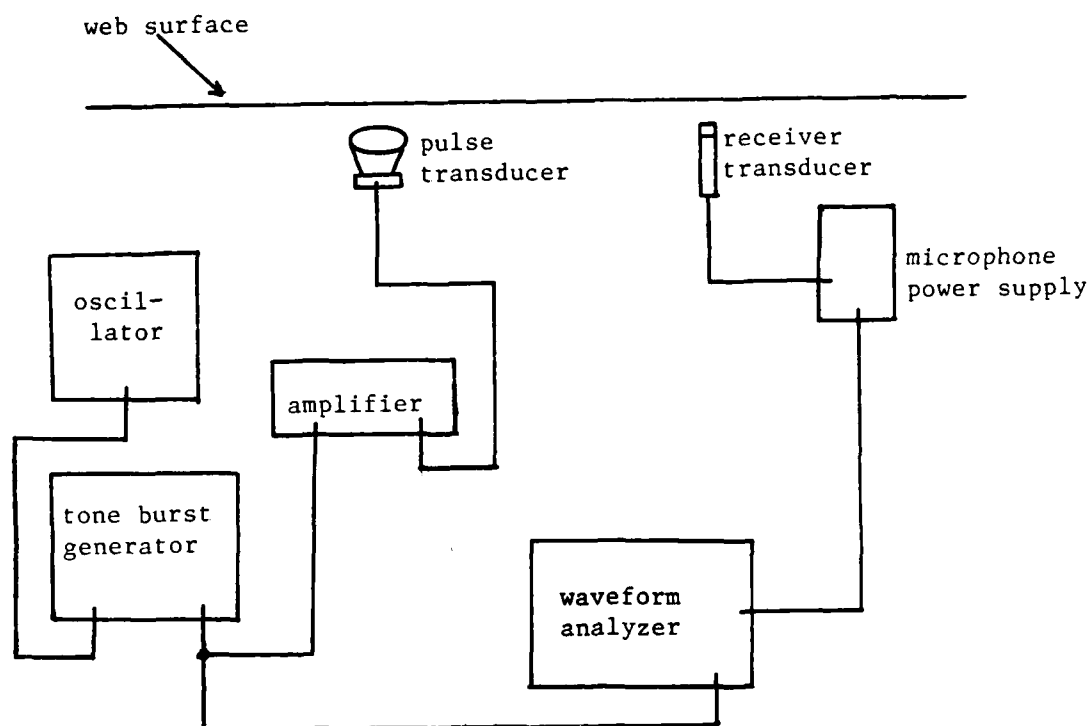Figure 3.1 System Diagram, Standing Wave.

web surface

Figure 3.2 System Diagram, Propagation Wave.

and sent to the pulse transducer. The microphone was used as a

receiver transducer, and the signal was sent to a universal waveform

analyzer for analysis. For both experiments, a frame was built that

allowed for a static web to be stretched to different tensions. One

end of the web was held by a clamp, and the other end was rolled around

a bar which could be turned and held in place by a ratchet device to

provide control of tension. A filar telescope was then used to make

measurements for determining the web tension.

3.2 Experimental Procedure

3.2.1 Standing Wave

The standing wave was obtained by using the oscillator and speaker combination to drive the web to resonance. Large speakers were used to obtain the coupling needed between the speaker and the web. When the web was at resonance, it was vibrating in a manner shown in Figure 3.3. Because the sound in the web was louder at wave
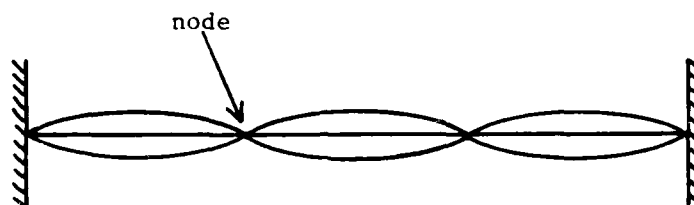

Figure 3.3 Standing Wave.

peaks, and almost silent at nodes, the microphone could be easily used to determine the number of nodes in the web. This was done by passing the microphone over the web surface and watching the signal trace on the oscilloscope. Since the sound in the web was lowest at the nodes, the oscilloscope trace was lowest when the microphone was over the node. Therefore, the number of nodes over the length of the web could easily be counted. The wave length could then be calculated through the use of Eq. 3.1. The oscillator frequency (excitation frequency) along with the wave length could then be used to calculate the sonic

$$\lambda = 2 \left[\frac{\text{no of nodes} + 1}{L} \right] \qquad \text{Eq. 3.1}$$

velocity in the web for a particular tension through Eq. 3.2. In these

equations, L is the web length, λ is the wave length, f is the excita-

tion frequency, and c is the sonic velocity. The tension of the web

$$c = f * \lambda \qquad \text{Eq. 3.2}$$

was calculated by placing a known weight across the center of the web

and using the filar telescope to measure the deflection of the web

(Eq. 3.3). In this equation, F is the force exerted by the known

weight, δ is the web deflection, and T is the web tension. This

$$T = \frac{F * L}{4 * \delta} \qquad \text{Eq. 3.3}$$

equation is good for small deflections and assumes that the tension in

the web does not change with the addition of the weight (see Figure
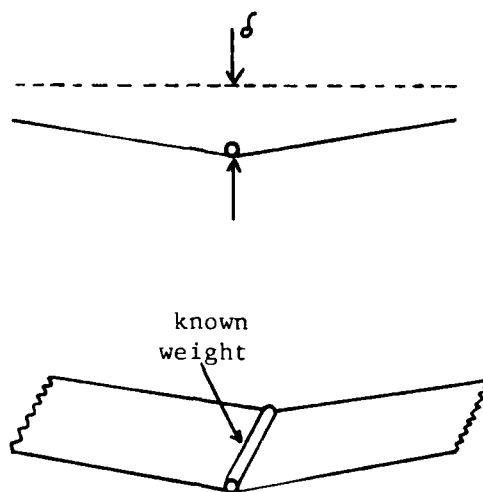
3.4).

Figure 3.4 Tension Measurement Technique.

3.2.2 Propagating Wave

The propagating wave experiments incorporated the tone burst generator and an amplifier between the oscillator and the pulse transducer. Three types of speakers were used as pulse transducers. The first was a line array of 3.5 inch sub-wolfer speakers. The speakers were attached to a plate and positioned such that a 0.25 inch slot was directly over the center of the speakers. The second was a line piezo type tweeter, and the third was a 0.75 inch hard dome tweeter. The transducer was placed directly beneath the web and pulsed with the signal from the amplifier (see Figure 3.5). The signal was then picked up down the web by the receiver transducer (microphone). The waveform analyzer was used to measure the difference between the time that the signal was sent to the pulse transducer and the time
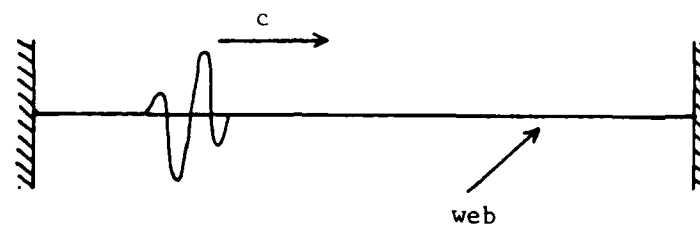
Figure 3.5 Propagating Wave.

that the signal was received by the receiver transducer. By knowing

this time difference and the distance between the two transducers, the

velocity of wave propagation (sonic velocity) could easily be calculated

through Eq. 3.4. In this equation, d is the distance between the

transducers, t is the time difference, and c is the velocity of wave

propagation.

$$c = \frac{d}{t} \qquad\qquad \text{Eq. 3.4}$$

CHAPTER IV

RESULTS

4.1 Standing Wave

The standing wave experiments were conducted to demonstrate the dependency of the sonic velocity (speed of wave propagation) on web tension. These experiments used a polypropolene web of two widths and lengths. The results are shown in Figure 4.1 (the data for the plots is shown in Appendix A). They all have the same shape and prove the same dependencies. As the excitation frequency increases, the sonic velocity increases for a given tension, and as tension increases, the sonic velocity increases for a given excitation frequency. The curve over toward the higher tensions may be explained by analyzing an equation developed by Morse and Ingard.[8] Their equation (Eq. 4.1) was

$$K = k_m \left[1 + \frac{\rho}{\sqrt{k_m^2 - k^2}} \right] \qquad \text{Eq. 4.1}$$

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[8] P. M. Morse and K. U. Ungard, Theoretical Acoustics (New York: McGraw-Hill Book Company, 1968), p. 690.

SONIC VELOCITY vs. TENSION
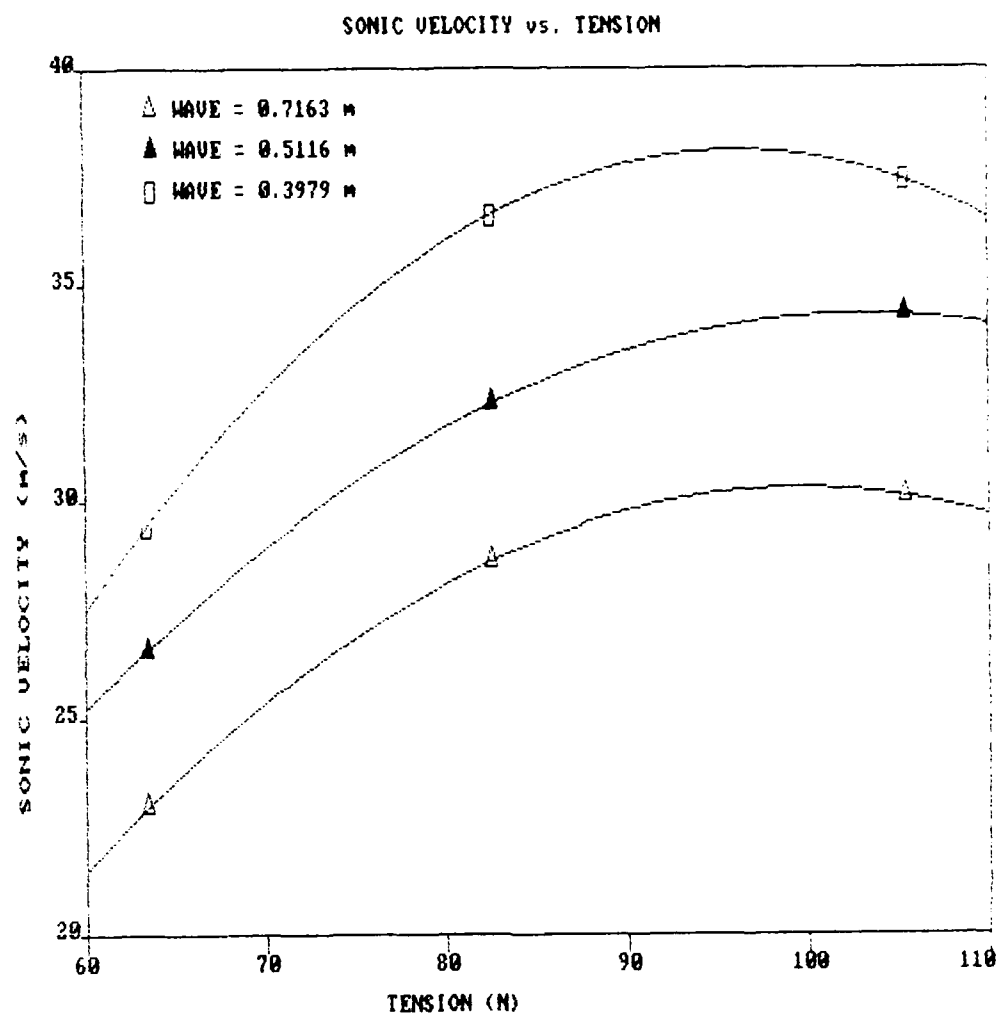
The Regression Polynomial of Line 1 -

$$(2.148E+01) + (2.233E+01)*X + (-1.416E+01)*X^2$$
The Variance - 1.655E-10

The Regression Polynomial of Line 2 -

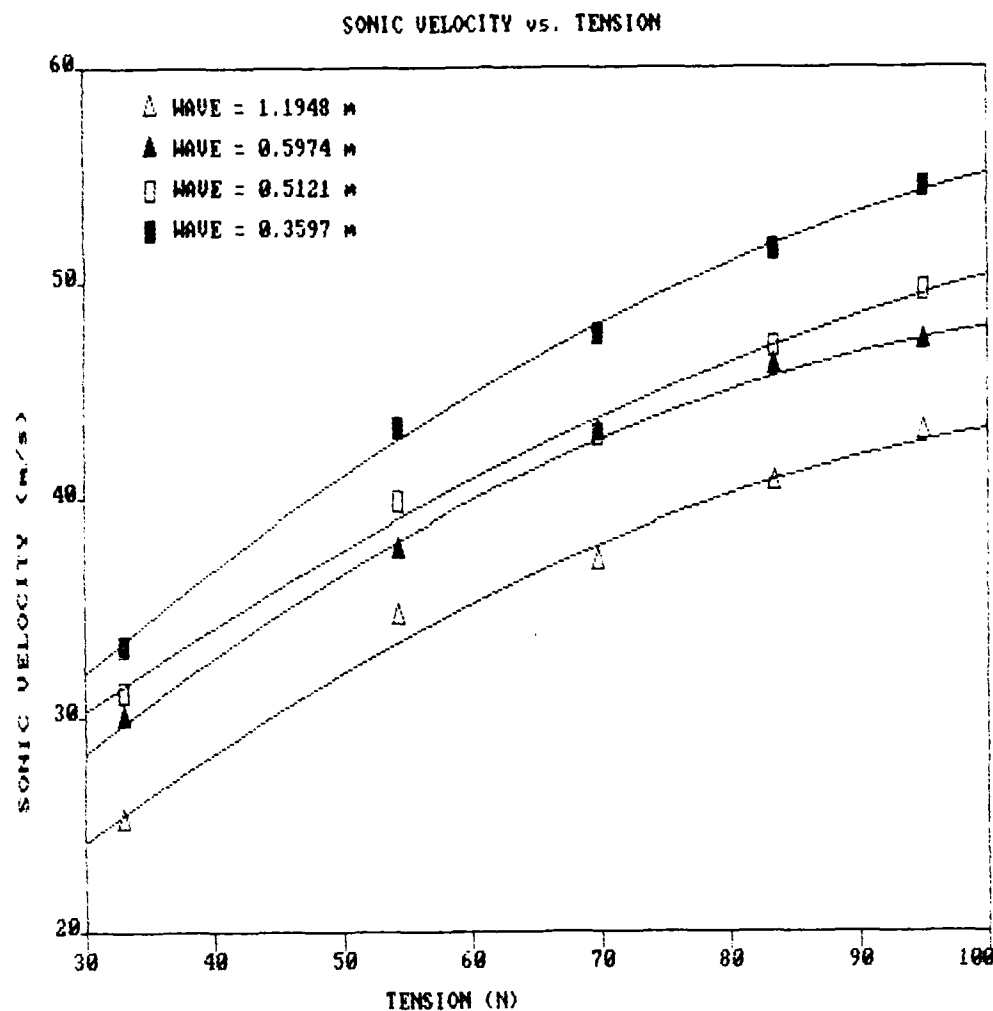$$(2.524E+01) + (2.107E+01)*X + (-1.224E+01)*X^2$$
The Variance - 9.216E-12

The Regression Polynomial of Line 3 -

$$(2.756E+01) + (2.925E+01)*X + (-2.029E+01)*X^2$$
The Variance - 3.537E-10

Figure 4.1.a Sonic Velocity vs Tension For Web
Width of 49.53 cm and Length of 179.07 cm.

SONIC VELOCITY vs. TENSION

The Regression Polynomial of Line 1 -

$$(2.414E+01) + (3.105E+01)*X + (-1.201E+01)*X^2$$

The Variance - 4.891E-01

The Regression Polynomial of Line 2 -

$$(2.835E+01) + (3.262E+01)*X + (-1.306E+01)*X^2$$

The Variance - 1.033E-01

The Regression Polynomial of Line 3 -

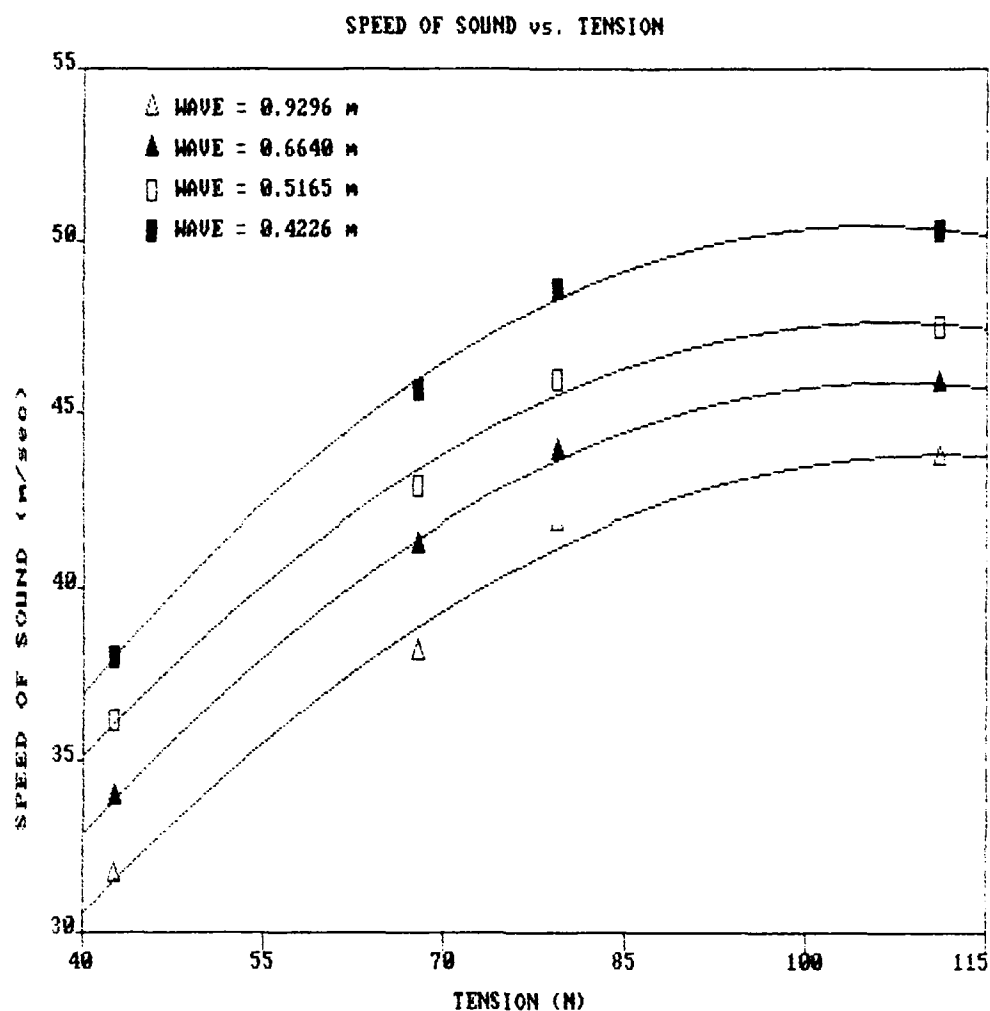$$(3.027E+01) + (2.833E+01)*X + (-8.268E+00)*X^2$$

The Variance - 2.502E-01

The Regression Polynomial of Line 4 -

$$(3.206E+01) + (3.486E+01)*X + (-1.185E+01)*X^2$$

The Variance - 1.309E-01

Figure 4.1.b Sonic Velocity vs Tension For Web
Width of 21.59 cm and Length of 179.07 cm.

SPEED OF SOUND vs. TENSION

The Regression Polynomial of Line 1 -

$$(3.054E+01) + (2.788E+01)*X + (-1.467E+01)*X^2$$

The Variance - 2.732E-01

The Regression Polynomial of Line 2 -

$$(3.287E+01) + (2.893E+01)*X + (-1.608E+01)*X^2$$

The Variance - 2.346E-02

The Regression Polynomial of Line 3 -

$$(3.514E+01) + (2.799E+01)*X + (-1.568E+01)*X^2$$

The Variance - 1.184E-01

The Regression Polynomial of Line 4 -

$$(3.695E+01) + (3.088E+01)*X + (-1.770E+01)*X^2$$

The Variance - 5.450E-02

Figure 4.1.c   Sonic Velocity vs Tension For Web
Width of 21.59 cm and Length of 232.41 cm.

modified to show the dependency of sonic velocity on web tension and excitation frequency. This was done by using the following relationships (the web characteristics are for polypropolene):

$$K = \frac{\omega}{c}$$

$$k_m = \frac{\omega}{c_m}$$

$$\rho = 1.1766 \; \frac{kg}{m^3}$$

$$c_{air} = 343 \; \frac{m}{s} \; (\delta \; 20° \; C)$$

$$c_m = c_{vacuo} = \sqrt{\frac{T}{\sigma}}$$

$$\omega = 2 \pi F$$

$$t = 22.86 \times 10^{-6} \; m \quad \text{(web thickness)}$$

specific gravity (S.G.) = 0.91

$$\sigma = (t) \; (S.G.) = 20.8 \times 10^{-3} \; \frac{kg}{m^2}$$

w = 0.2159 m (web width)

Through the use of these numbers and some minor algebra, Morse and Ingard's equation becomes Eq. 4.2 where F is the excitation frequency,

$$SQT = \sqrt{\frac{4.492 \times 10^{-3}}{T} - 8.5 \times 10^{-6}}$$

$$c = 14.92 \sqrt{T} \left[\frac{F(0.1307) * SQT}{1.1766 + F(0.1307) * SQT} \right] \qquad \text{Eq. 4.2}$$

T is the tension in newtons, and c is the sonic velocity in meters per second. Figure 4.2 shows the results of this equation for four different frequencies, and Figure 4.3 shows a 3-D representation of the equation. Both show a sort of parabolic shape which coincides with the experimental results.
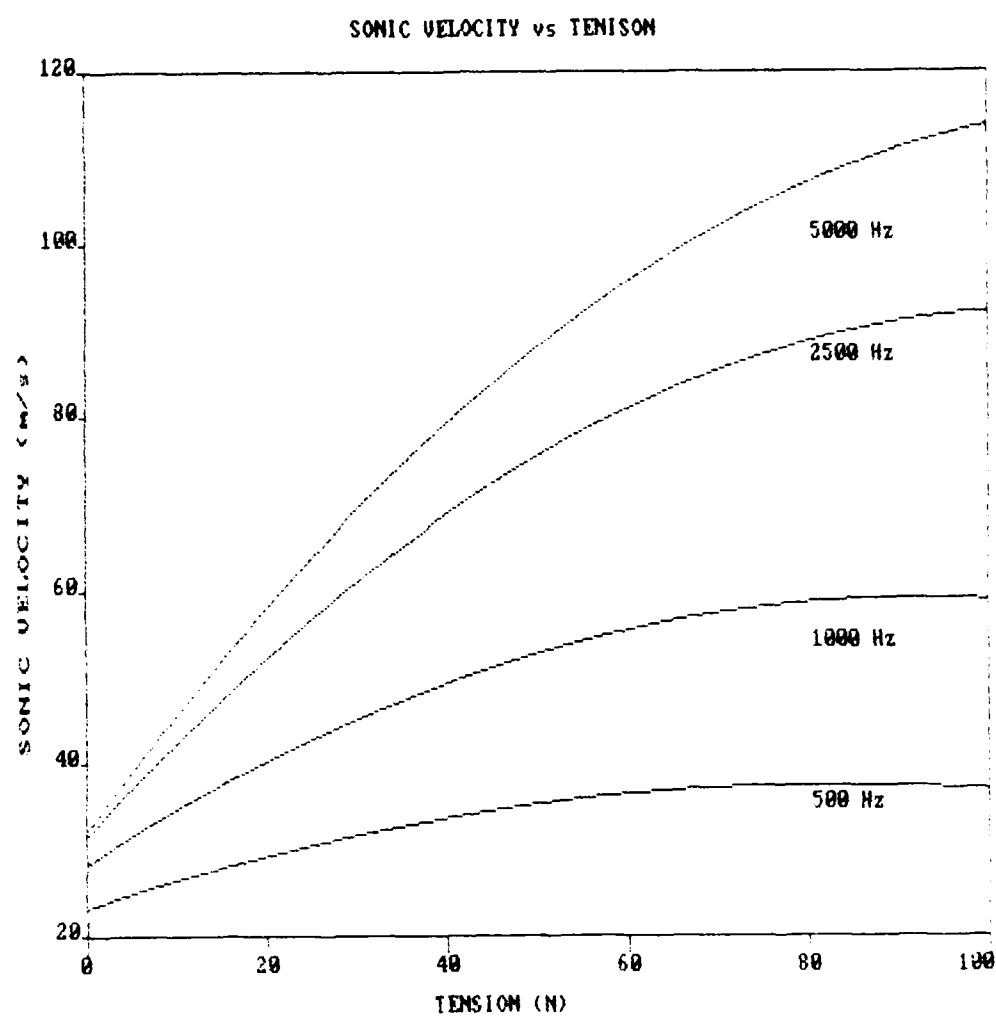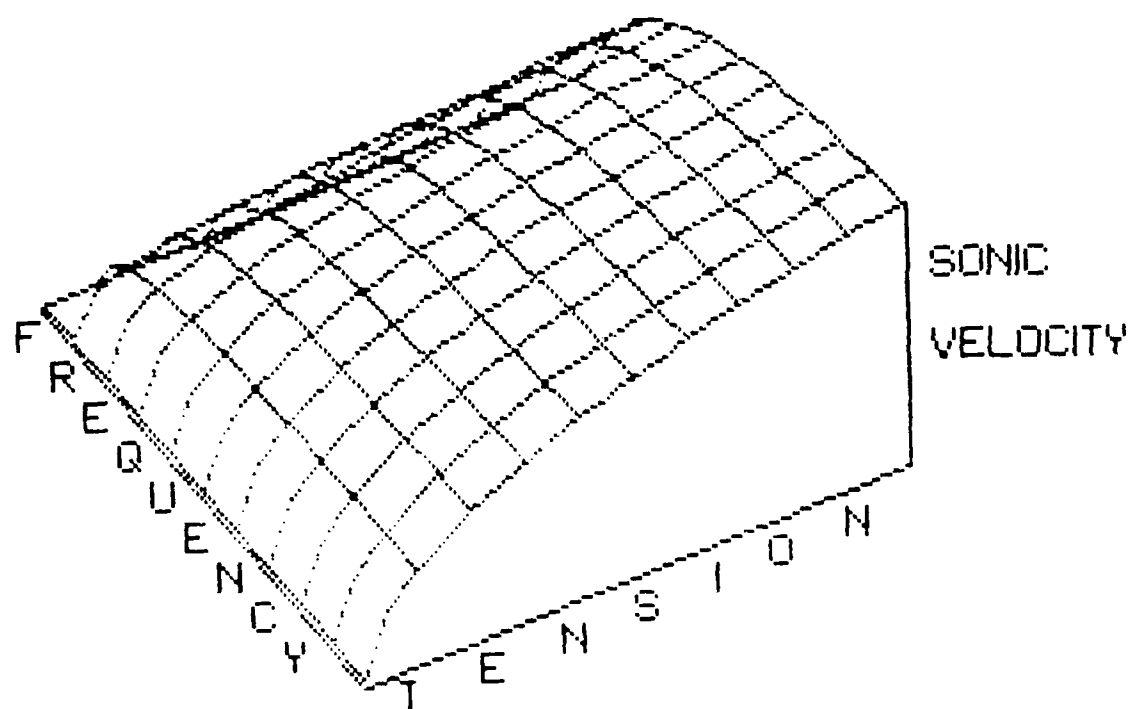
Figure 4.2 Graph of Eq. 4.2.

Figure 4.3 3-D Graph of Eq. 4.2.

4.2 Propagating Wave

The propagating wave experiments were conducted for the same reasons that the standing wave experiments were, however the measurement technique was different. The idea was to measure the time required for a propagating wave to pass two points. The experiments were run on the 21.59 cm web. Figure 4.4 shows the plot of the results and the regression polynomials for the lines (the data is shown in Appendix B). These results show the same trends as the standing wave results did. As the frequency increases, the sonic velocity increases for a given tension, and as the tension increases, the sonic velocity increases for a given frequency. The added line across the top was produced through the use of equation 2.3 which does not take into account the effects of air mass on the web. Thus, two facts can be noted from observing the difference between the theoretical and the experimental. (1) As frequency increases, the effect of air mass decreases, and (2) as tension increases, the effect of air mass increases. Assuming that Eq. 2.3 gives an accurate representation of sonic velocity in a vacuum and that an air mass term can be added to it (Eq. 4.3) to represent the sonic velocity in air, then Eq. 4.4 can be developed to determine the air mass effects on the experimental results. The results of this comparison are shown in Figure 4.5 and confirm the two previous observations concerning air mass effects with respect to tension and frequency. Antti Pramila[9] conducted some research into the effects of air mass on the web and concluded that

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[9] Antti Pramila, "Sheet Flutter and the Interaction Between Sheet and Air," Tappi, vol. 69, no. 7 (July 1986), pp. 70-74.

SONIC VELOCITY vs TENSION
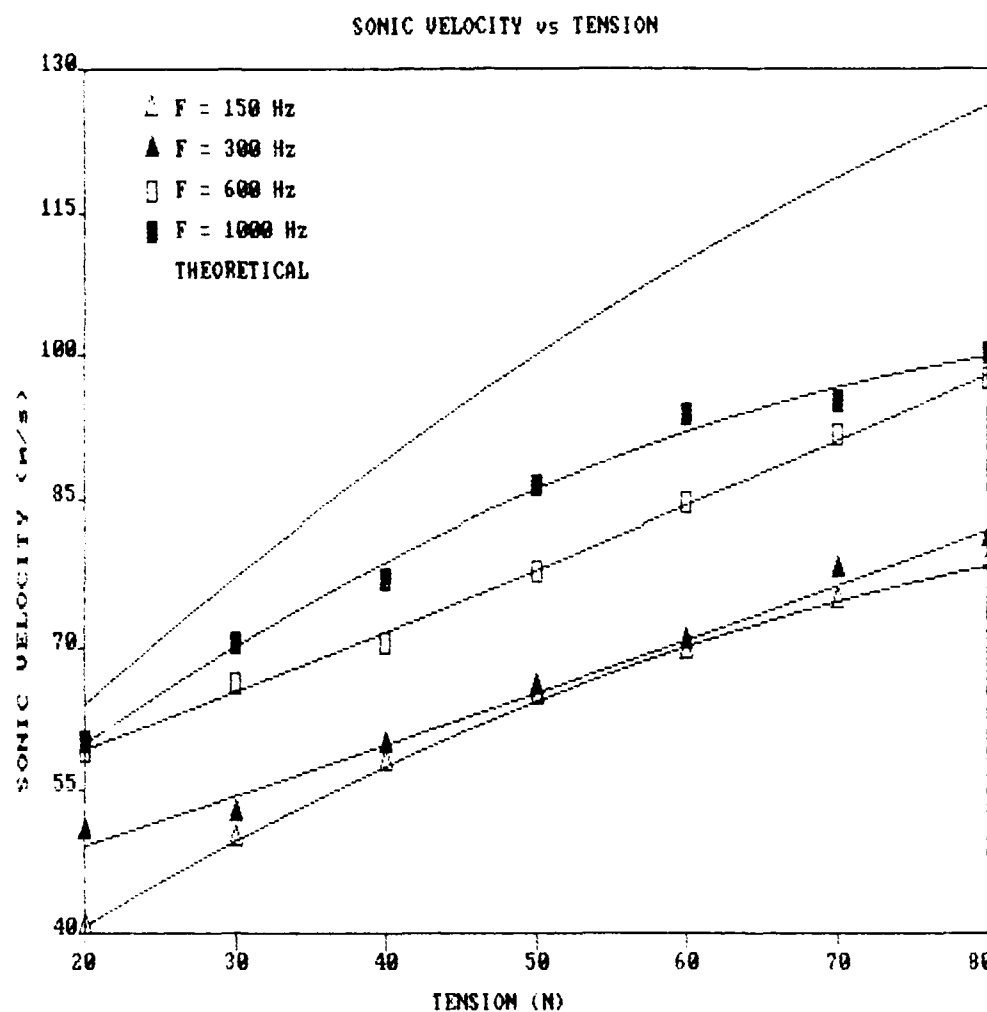
The Regression Polynomial of Line 1 -
$$(4.076E+01) + (5.639E+01)*X + (-1.880E+01)*X^2$$
The Variance - 1.170E-01

The Regression Polynomial of Line 2 -
$$(4.923E+01) + (3.086E+01)*X + (1.979E+00)*X^2$$
The Variance - 1.208E+00

The Regression Polynomial of Line 3 -
$$(5.928E+01) + (3.575E+01)*X + (3.053E+00)*X^2$$
The Variance - 3.544E-01

The Regression Polynomial of Line 4 -
$$(5.986E+01) + (6.507E+01)*X + (-2.493E+01)*X^2$$
The Variance - 1.404E+00

Figure 4.4 Sonic Velocity vs Tension
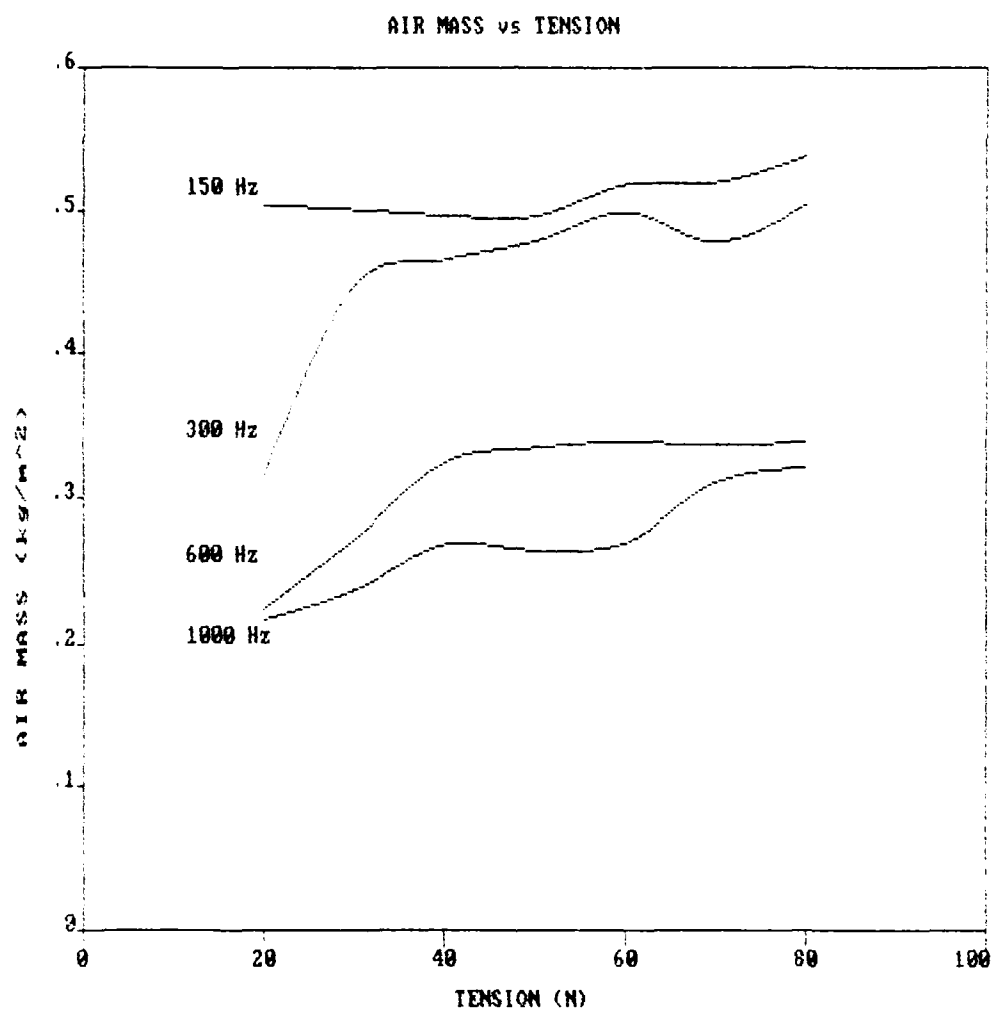For Web Width of 21.59 cm.

Figure 4.5 Air Mass Analysis.

they could be quite significant. Figure 4.6 shows the output of the
waveform analyzer for increasing distances between the pulse transducer
and the receiving transducer. These results were obtained by using the
3.5 inch cone type speaker line array transaucer and pulsing it at
600 Hz (the natural frequency of the 3.5 inch speaker was about 150 Hz).
Four observations can be easily made from this figure. (1) The first
trace was at a distance of one foot and shows the pulse frequency
riding on top of the speaker natural frequency, and the higher fre-
quency at the start of the trace was produced by the sound moving
through the air (600 Hz). Since the higher frequency pulse is faster
than the lower frequency, the higher frequency begins to pull away with
increasing distance. (2) The pulse attenuates with increasing distance.
Figure 4.7 shows the relationship of attenuation with distance.
(3) The higher the frequency is, the faster the signal attenuates.
(4) Since a sharply defined pulse is easier for measuring equipment
to distinguish, the larger the distance is between the pulse transducer
and the receiving transducer, the more difficult it is to make accurate
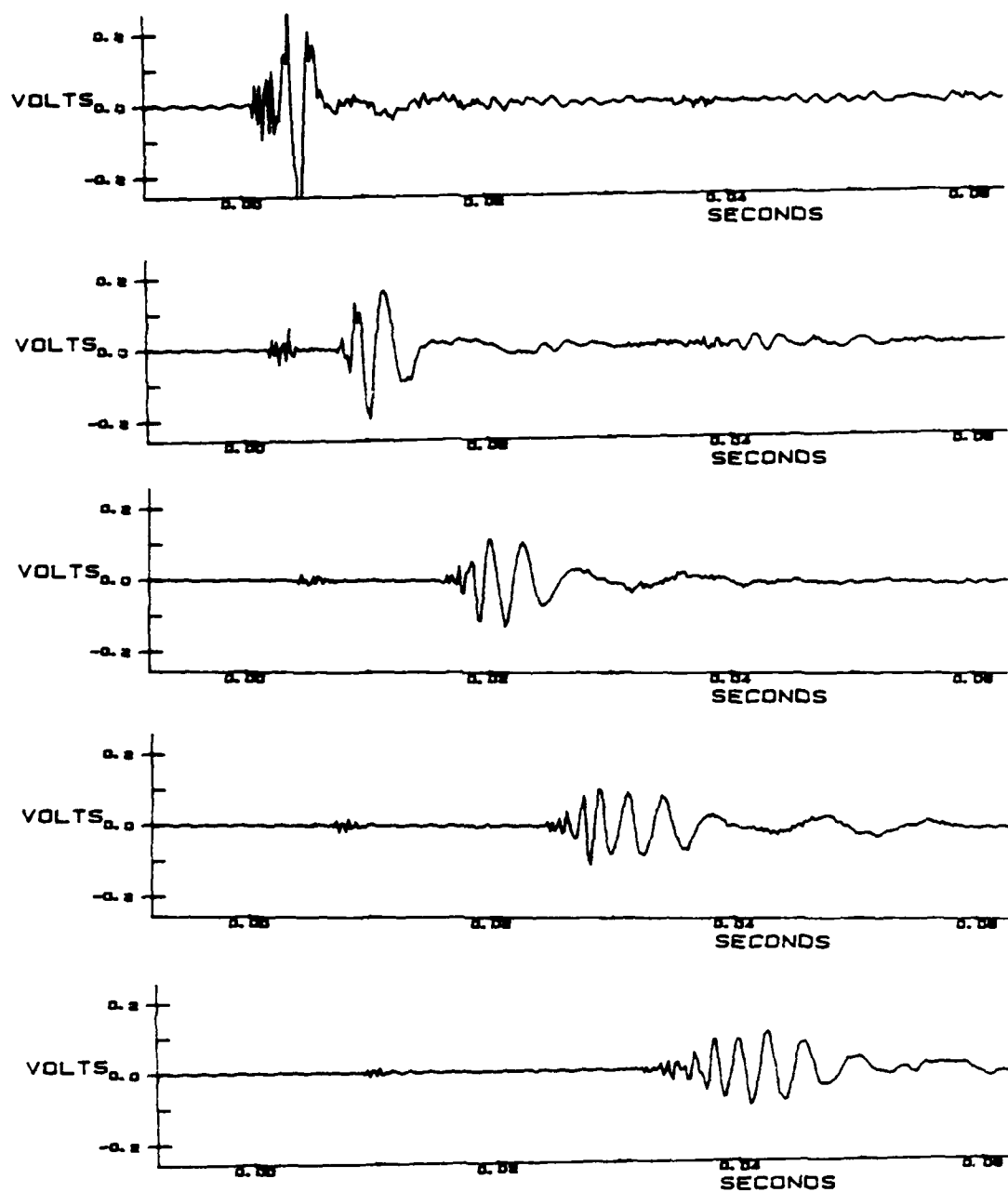measurements.

Figure 4.6 Waveform Analyzer Plots For
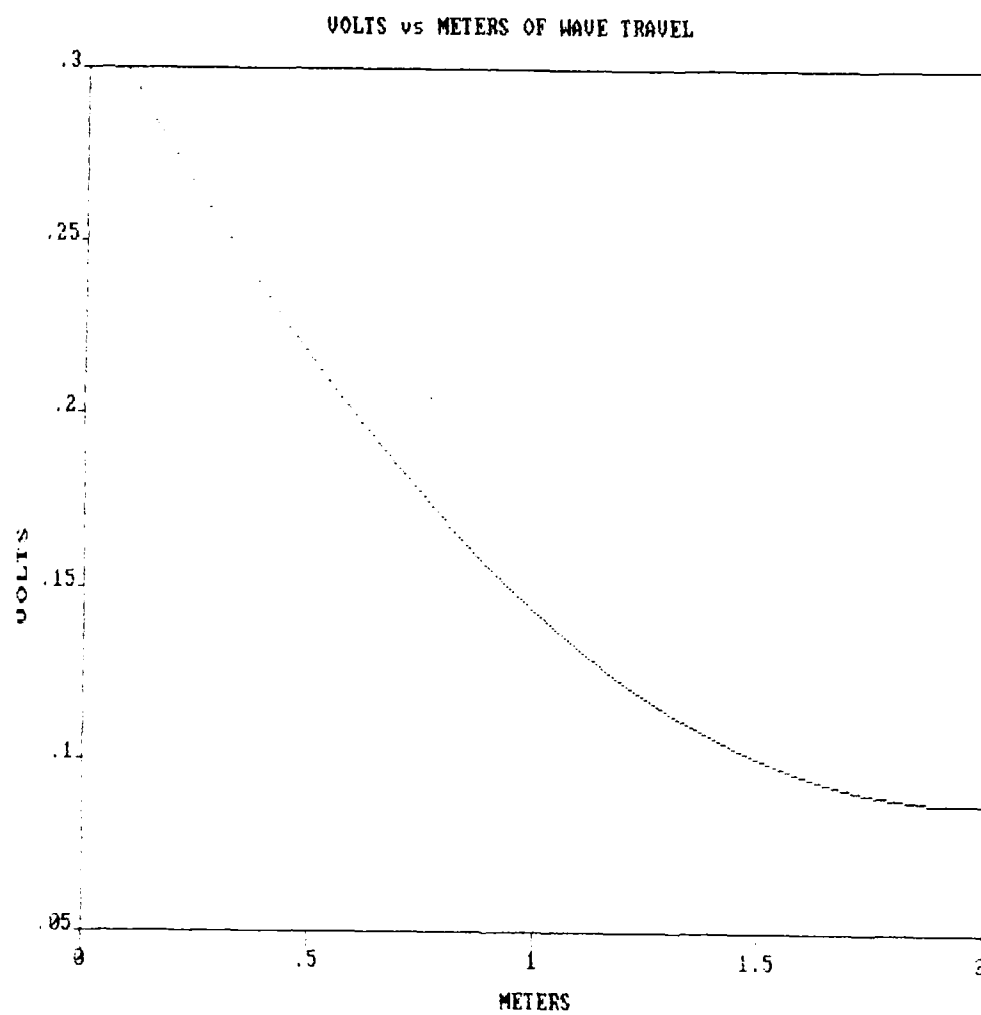Increasing Measurement Distance.

Figure 4.7 Attenuation of Pulse Signal
With Increasing Distance.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Both the standing wave and propagating wave approach can produce the desired results. However, as Senko and Thorpe[7] found in their experiments with sonic velocity, in the propagating wave approach, it is very difficult to distinguish the desired signal from noise either in the web or in the air, whereas the standing wave approach can provide a continuous signal which will be easier to process. Also, the time frame for measurement of the pulse wave can be very small, therefore, introducing uncertainty. Since the standing wave approach does not have this restriction, a high degree of certainty can be obtained. In either case, there are a few aspects that need to be kept in mind.

Transducers
> Both the transmitting and receiving transducers need a lot of work. Piezoelectric type transducers seem to be the most promising especially for the propagating wave approach. They would also be a good choice for the standing wave so long as a good coupling between the transducer and the web can be achieved.

Air mass
> At low frequencies, the effect of the weight of the air that is clinging to the web can be significant. The air could actually weigh more than the web, therefore, greatly damping the web vibrations. This influence decreases as frequency increases.

Frequency
> The sonic velocity in a web is definitely dependent on the excitation frequency.

Wave attenuation

As the wave travels down the web it atteruates or decreases in strength. This effect increases with increasing frequency. Also, as the wave travels, it seems to become less "crisp" (i.e. it spreads out and becomes harder to distinguish).

Speakers

If speakers are used as transducers, there are two facts to keep in mind. (1) The minimum wave length produced may be limited to twice the diameter of the speaker for standing wave systems. (2) In propagating wave experiments, it was found that the speaker must be pulsed at its natural frequency. If not, there will be two wave forms produced. Assuming the pulse frequency is higher than the speaker natural frequency, the higher pulse frequency will start out riding on top of the lower speaker natural frequency. As the wave travels, the higher frequency will move faster than the lower one and the two frequencies will eventually separate. This adds confusion to the analysis of the sonic velocity.

Since the velocity of the web itself will affect the sonic velocity measurements, both approaches will need to incorporate a means for determining the web velocity. This can easily be done by using an idler roll, or two receiving transducers could be used (see Figure 5.1) to extract the web velocity. Equation 5.1 was taken from Klosky[10]
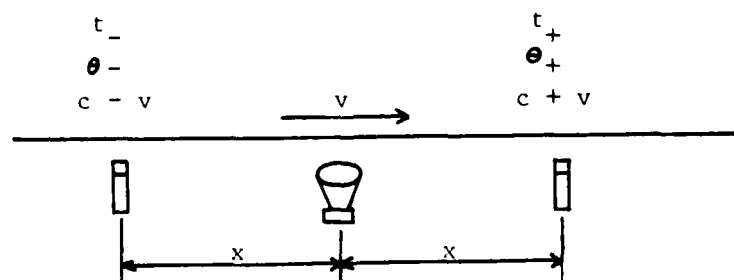

Figure 5.1   Transducer Diagram.

[10]H. Klosky, Stress Waves in Solids (New York: Dover Publications, Inc. 1963), p. 143.

$$\theta = \frac{\omega x}{c} \qquad \text{Eq. 5.1}$$

and can be rearranged to give the desired information. In this equation, θ is the phase shift angle (in radians), ω is 2 times the excitation frequency, x is the distance between the source and the receiver, and c is the sonic velocity. In the case of the moving web, the equation becomes Eq. 5.2, and v is the web velocity. The

$$\theta = \frac{\omega x}{c \pm v} \qquad \text{Eq. 5.2}$$

transducer downstream will see the web velocity term added, and the transducer upstream will see the term subtracted. The phase shift at the two points will be different with the one upstream labeled θ_+ and the one downstream labeled θ_-. By solving for v from both points and setting the two equations equal, Eq. 5.3 can be obtained which will be effective with the standing wave technique, and through Eq. 5.4, Eq. 5.5 for the propagating wave can be found. In Eq. 5.5, t is the time lapse between the transmission of the pulse and the reception of the pulse.

$$c = \frac{\omega x}{2} \left[\frac{\theta_+ + \theta_-}{\theta_+ \, \theta_-} \right] \qquad \text{Eq. 5.3}$$

$$\Delta\theta = \omega \, \Delta t \qquad \text{Eq. 5.4}$$

$$c = \frac{x}{2} \left[\frac{t_+ + t_-}{t_+ \, t_-} \right] \qquad \text{Eq. 5.5}$$

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APPENDIX A

STANDING WAVE DATA

Data for Figure 4.1.a. Web width of 49.53 cm and length of 179.07 cm. Sonic velocities are in meters per second (m/s).

Tension (N)	Wave Length (m)		
	0.7163	0.5116	0.3979
63.3792	22.9210	26.6047	29.4470
82.4693	28.6512	32.2326	36.6098
105.3069	30.0838	34.2791	37.4057

Data for Figure 4.1.b. Web width of 21.59cm and length of 179.07 cm. Sonic velocities are in m/s.

Tension (N)	Wave Length (m)			
	1.1948	0.5974	0.5121	0.3597
32.9084	25.0698	29.8445	31.2104	33.3070
54.3250	34.6205	37.6041	39.9077	43.3349
69.8464	37.0081	42.9761	42.9775	47.6326
83.4750	40.5895	45.9605	47.0706	51.5722
95.0688	42.9772	47.1543	49.6288	54.4373

Data for Figure 4.1.c. Web width of 21.59cm and length of 232.41 cm. Sonic velocities are in m/s.

	Wave Length (m)			
Tension (N)	0.9296	0.6640	0.5165	0.4226
42.5066	31.6078	33.8654	36.1526	38.0308
67.8158	38.1152	41.1697	42.8667	45.6367
79.3203	41.8338	43.8258	45.9655	48.5949
111.0484	43.6931	45.8179	47.5149	50.2851

APPENDIX B

PROPAGATING WAVE DATA

Data for Figure 4.4. Web width of 21.59cm. Sonic velocities are in m/s.

Tension (N)	Excitation Frequency (Hz)			
	150	200	600	1000
20	40.53	50.46	59.07	60.00
30	49.80	52.55	66.26	70.56
40	57.73	59.53	70.56	76.97
50	64.58	65.69	77.76	86.59
60	69.27	70.56	84.67	94.07
70	74.71	77.76	91.81	95.25
80	78.56	81.06	97.69	100.26

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